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State-Based Impact Damage Quantification Using Large Area Capacitive Sensors

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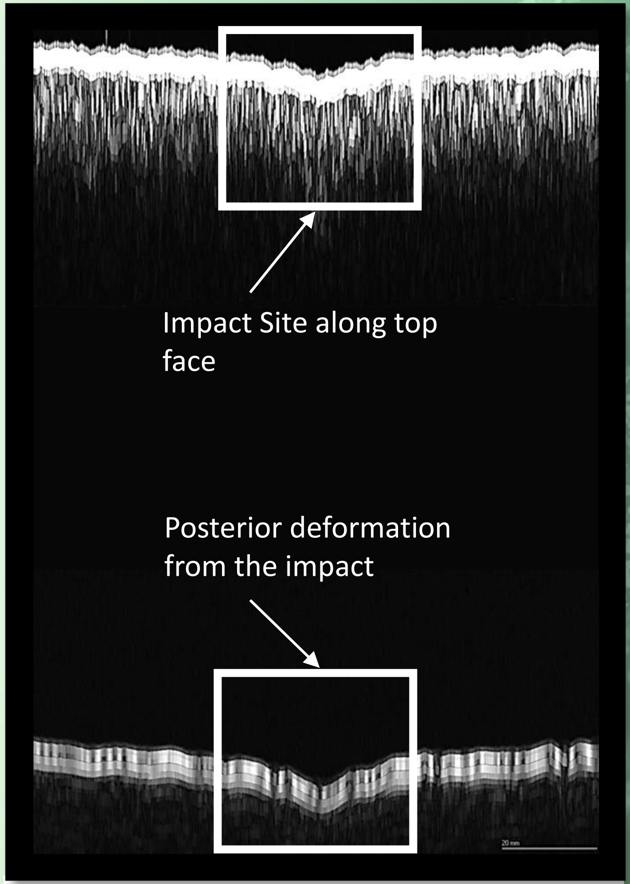
Introduction

- Impact damage detection is a significant issue in many fields
- Impacts can induce a permanent loss in the toughness
- NDT methods commonly incur non-trivial opportunity costs while parts are imaged
  - Ultrasonic
  - Acoustic Emission
  - Radiography



Ultrasonic image of composite blowout damage courtesy of iMAP's lab U of SC.

Motivation

NDT methods such as Ultrasonic imaging require removing pieces from service. The proposed use of the Soft Elastomeric Capacitor is as an in-situ sensing technology for live monitoring of composite damage.

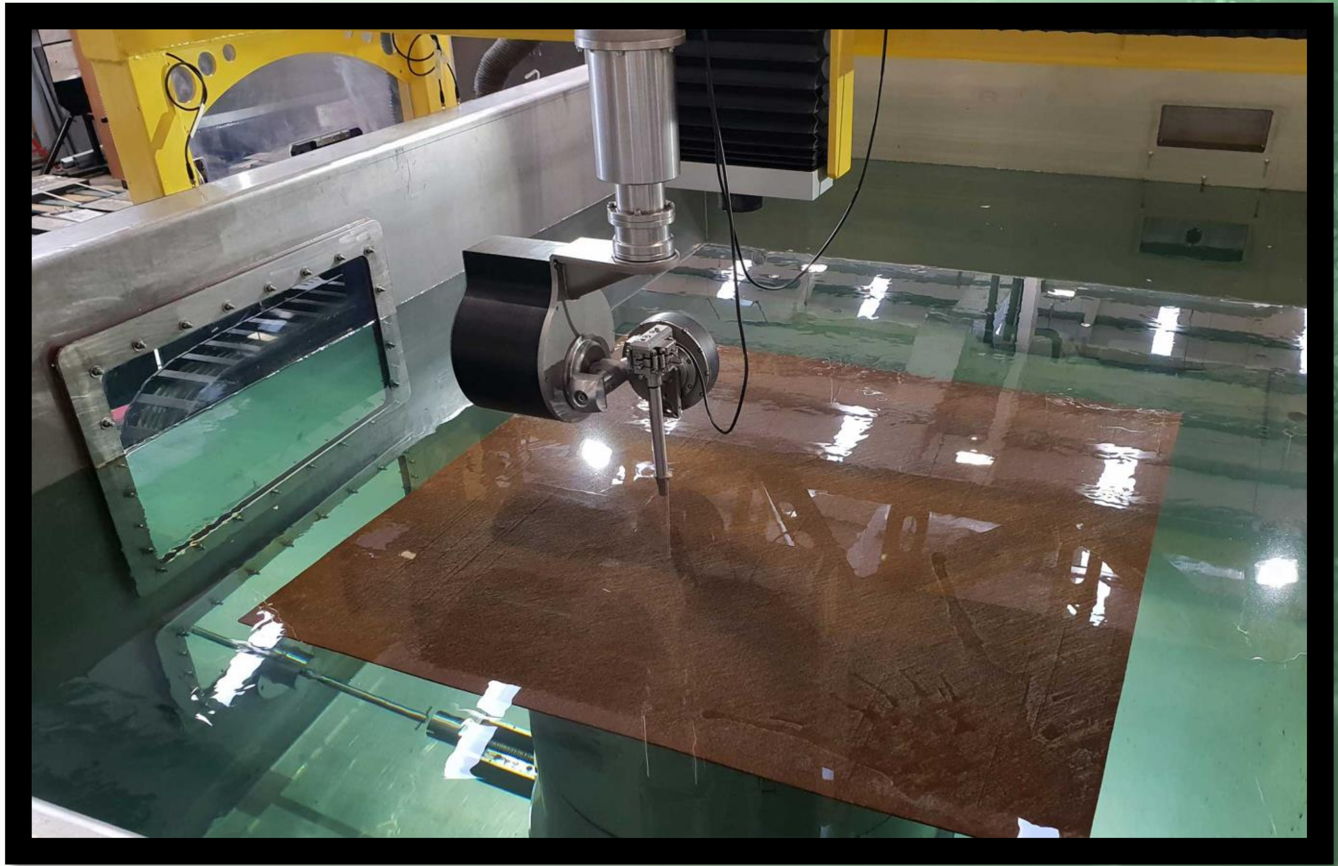
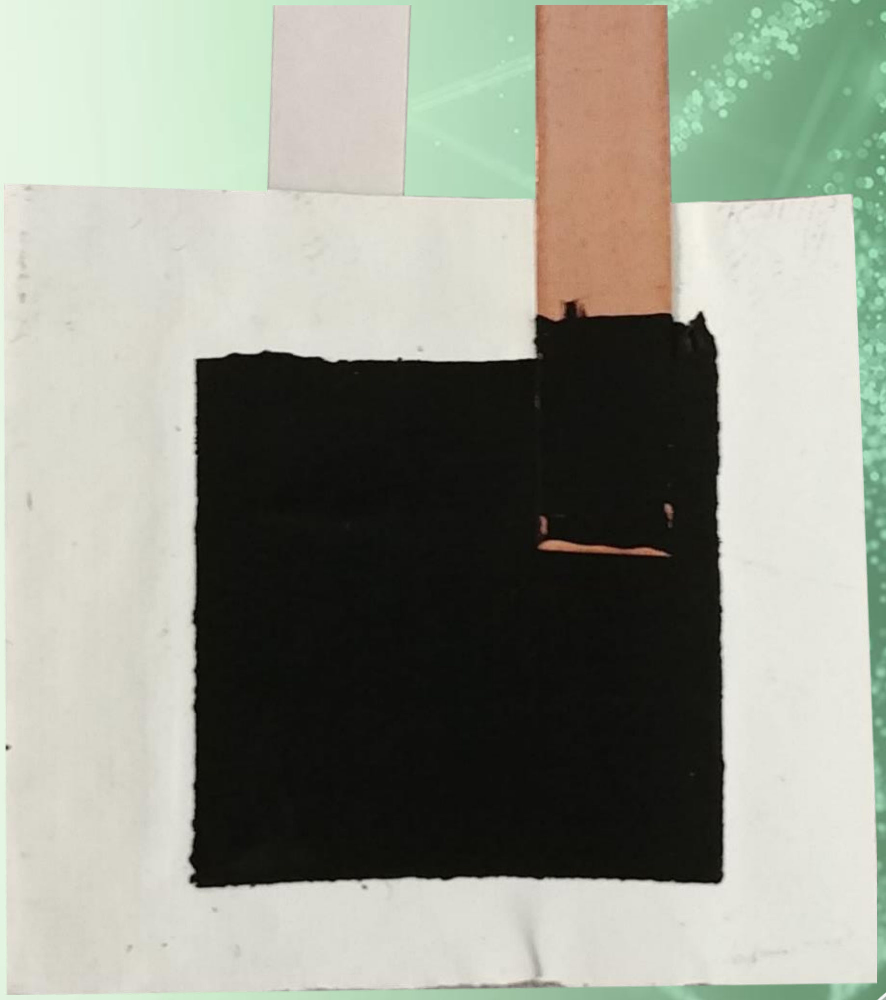


Image credit: https://www.twi-global.com/image-library/hero/ultrasonic-immersion-testing-20190723-142000.jpg

SEC

The soft elastomeric capacitor (SEC) is a flexible electronic capable of monitoring strain over large areas:

- Respond to changes in the sensor geometry
  - Linearly in sensor area and inversely to thickness
- Inherits the mechanical properties of an elastomer
- Functions as a parallel plate capacitor



Background Mathematics

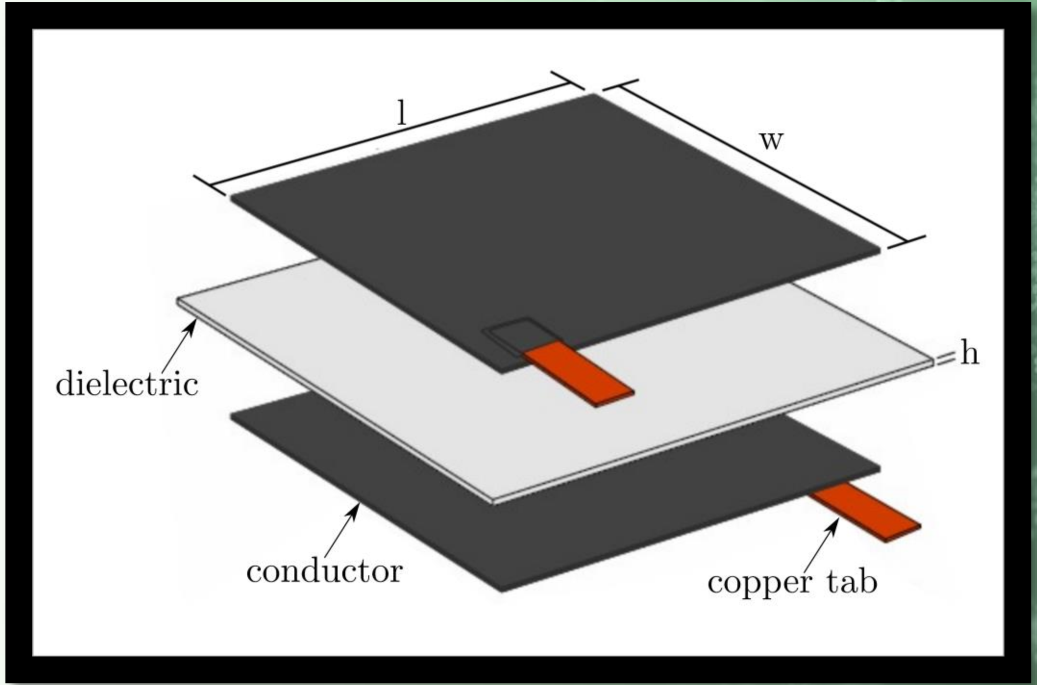
$$C = e_0\, e_r\, \frac{\mathrm{A}}{\mathrm{h}}$$

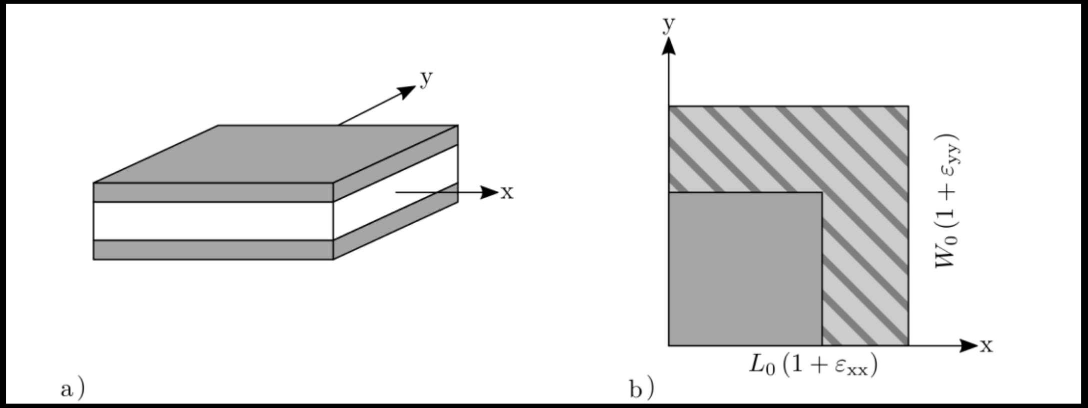
$$\frac{\Delta C}{C_0} = \frac{\left(\frac{\mathrm{A}_1}{\mathrm{h}_1} - \frac{\mathrm{A}_0}{\mathrm{h}_0}\right)}{\frac{\mathrm{A}_0}{\mathrm{h}_0}} = \frac{\mathrm{A}_1\mathrm{h}_0}{\mathrm{A}_0\mathrm{h}_1} - 1$$

Preservation of Mass:

$$\rho \mathrm{V}_1 = \rho \mathrm{V}_0 \quad \rightarrow \quad \mathrm{A}_1\mathrm{h}_1 = \mathrm{A}_0\mathrm{d}_0$$

$$\frac{\Delta C}{C_0} = \frac{\mathrm{A}_1\mathrm{A}_1\mathrm{h}_1\mathrm{h}_0}{\mathrm{A}_0\mathrm{A}_0\mathrm{h}_0\mathrm{h}_1} - 1 = \left(\frac{\mathrm{A}_1}{\mathrm{A}_0}\right)^2 - 1$$





Background Mathematics

Relating change in area to primary strain

$$A_1 = A_0(1+\varepsilon_{11})(1+\varepsilon_{22})$$

$$A_1 = A_0(\varepsilon_{11}\varepsilon_{22}+\varepsilon_{11}+\varepsilon_{22}+1)$$

Neglecting the squared term for small strains

$$A_1 \approx A_0\,(\varepsilon_{11}+\varepsilon_{22}+1)$$

$$\frac{\Delta C}{C_0} = \left(\frac{A_1}{A_0}\right)^2 - 1$$

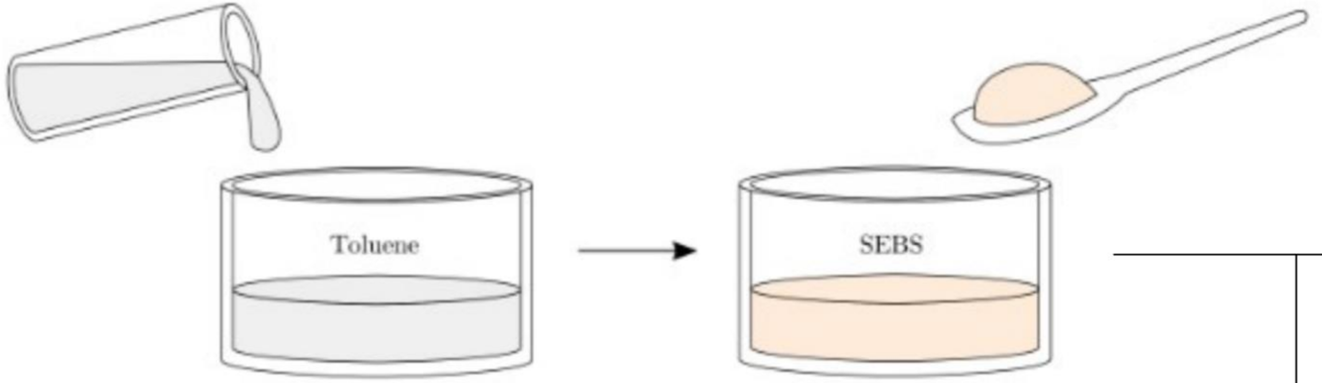
Substituting the area with strain relation

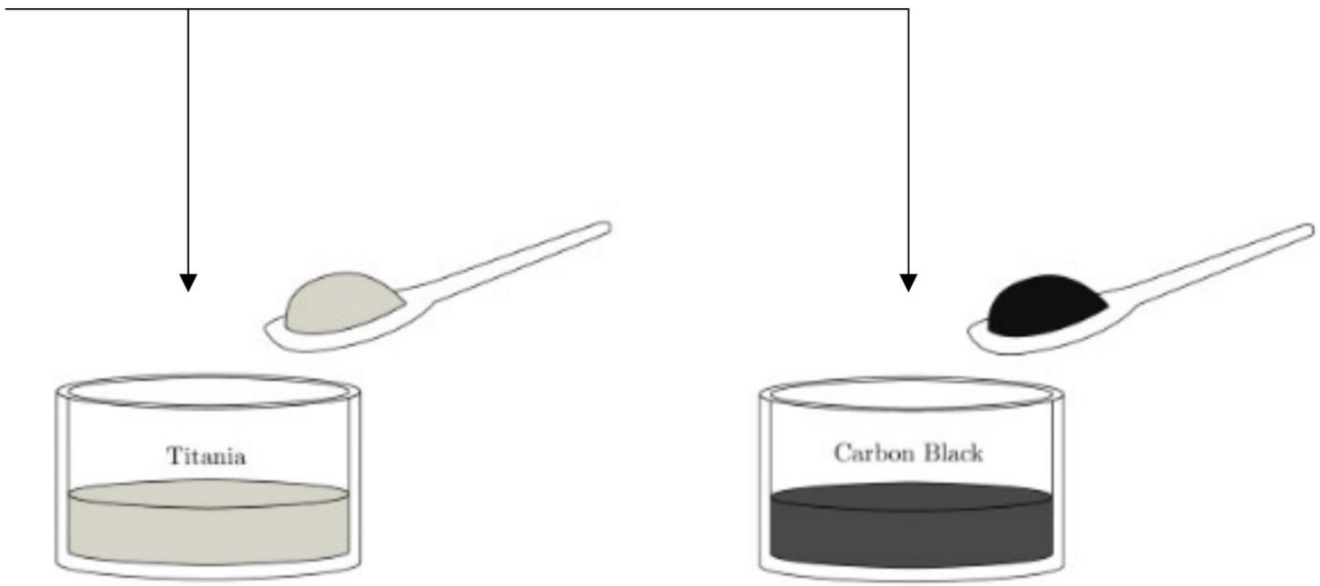
$$\frac{\Delta C}{C_0} \approx \left(\frac{A_0(\varepsilon_{11}+\varepsilon_{22}+1)}{A_0}\right)^2 - 1$$

$$\frac{\Delta C}{C_0} \approx \cancelto{0}{\varepsilon_{11}^2} + \cancelto{0}{\varepsilon_{22}^2} + 2(\varepsilon_{11}+\varepsilon_{22})$$

$$\frac{\Delta C}{C_0} \approx 2(\varepsilon_{11}+\varepsilon_{22})$$

Manufacture

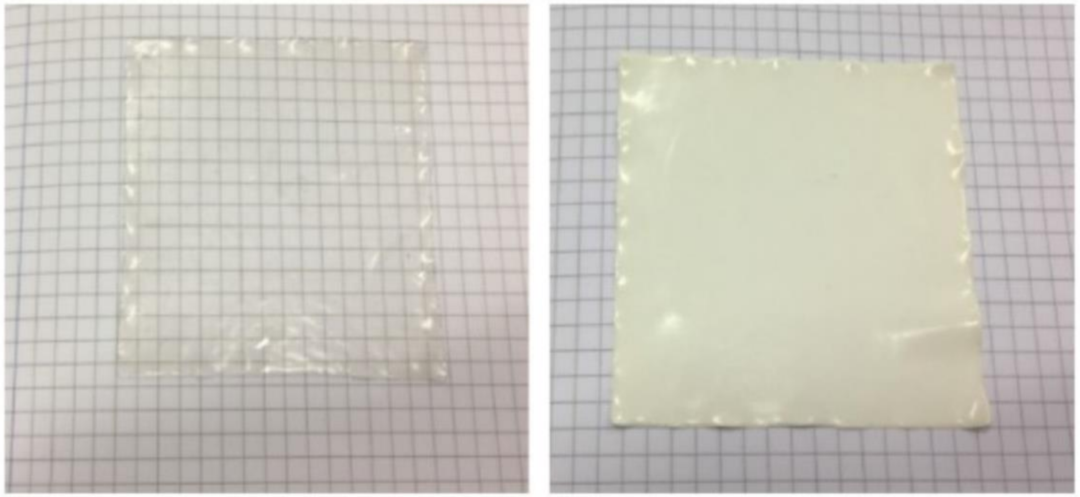




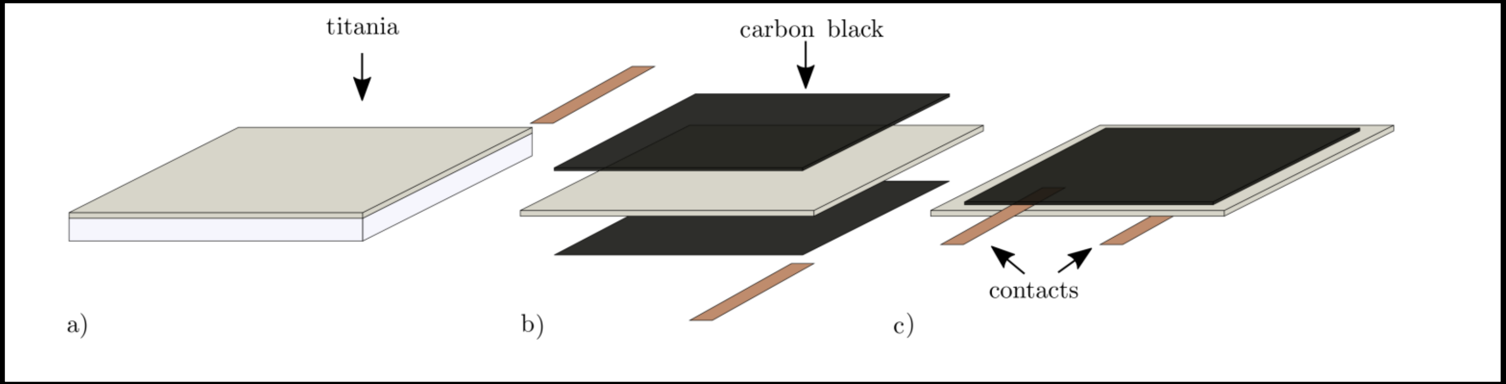
1) Dissolve SEBS in toluene

2*a*) Disperse Titania (TiO_2) by sonication in the SEBS solution

2*b*) Disperse Carbon Black (C) by sonication in the SEBS solution



Manufacture

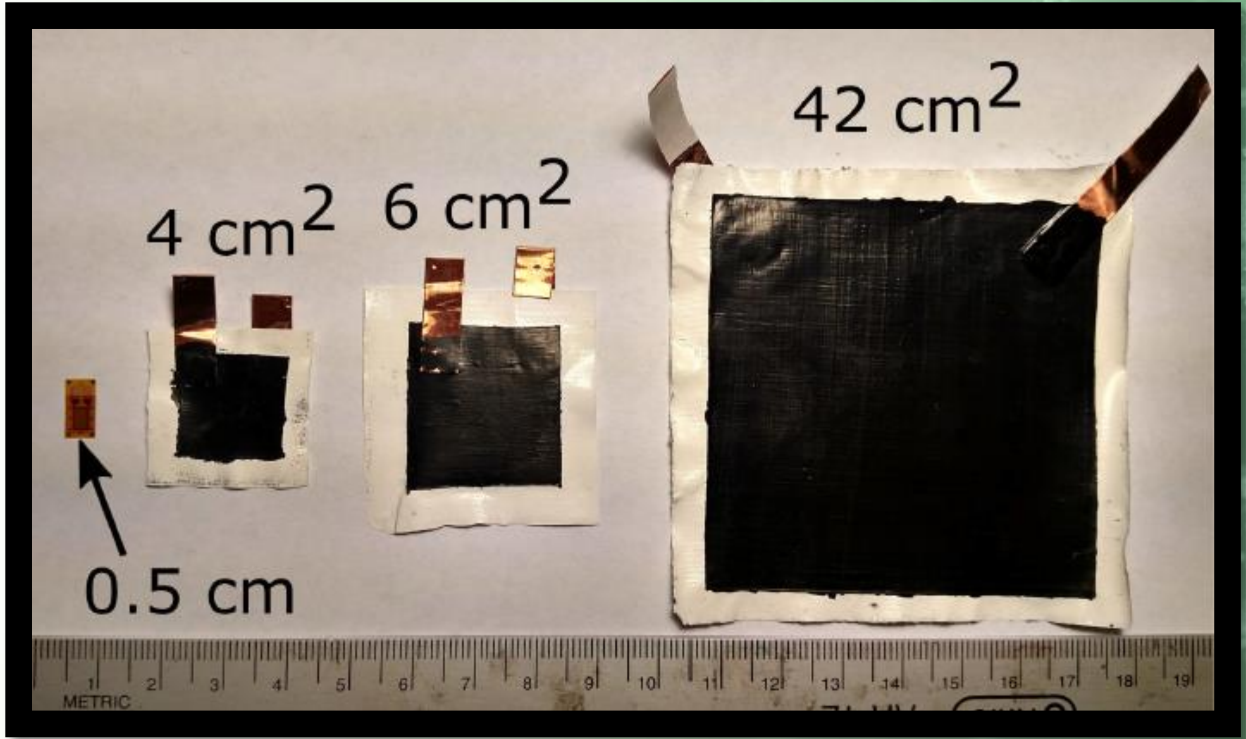


a) The dielectric is drop cast onto a glass pane
b) The carbon black SEBS solution is then painted onto the dielectric in progressive layers
c) Two copper tabs are used for metallic connections to connect to the data acquisition system

Manufacture

- The manufacture of the SEC makes the scaling of the sensor trivial

- The Elastomer matrix can extend up to 500% of its original length



Study Material

Glass Fiber Reinforced Plastic or (GFRP):

- Fiber orient: Random
- Fiber length: Short
- Matrix: Polyester
- Fiber material: Glass
- Dimension: [4 x 6 x 0.125] in^3

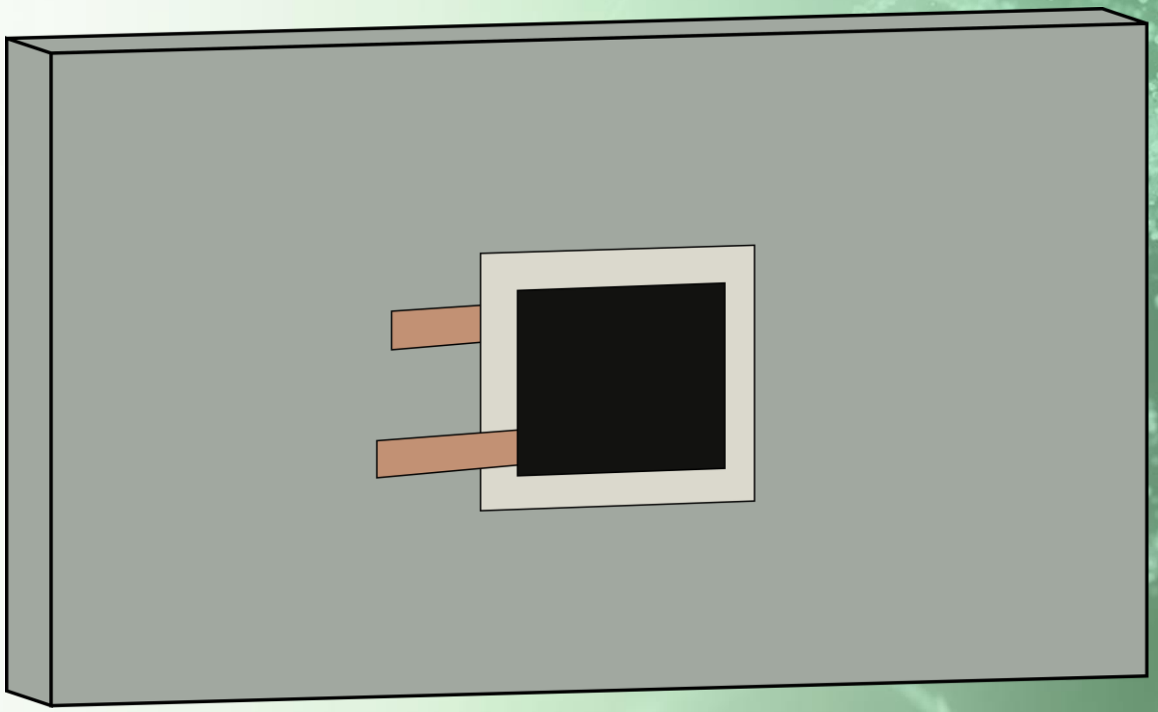
Behavioral Assumptions

Assumptions in elastic impact:

Initial impact energy is equal to the kinetic energy leaving the sample

Assumptions in plastic impact:

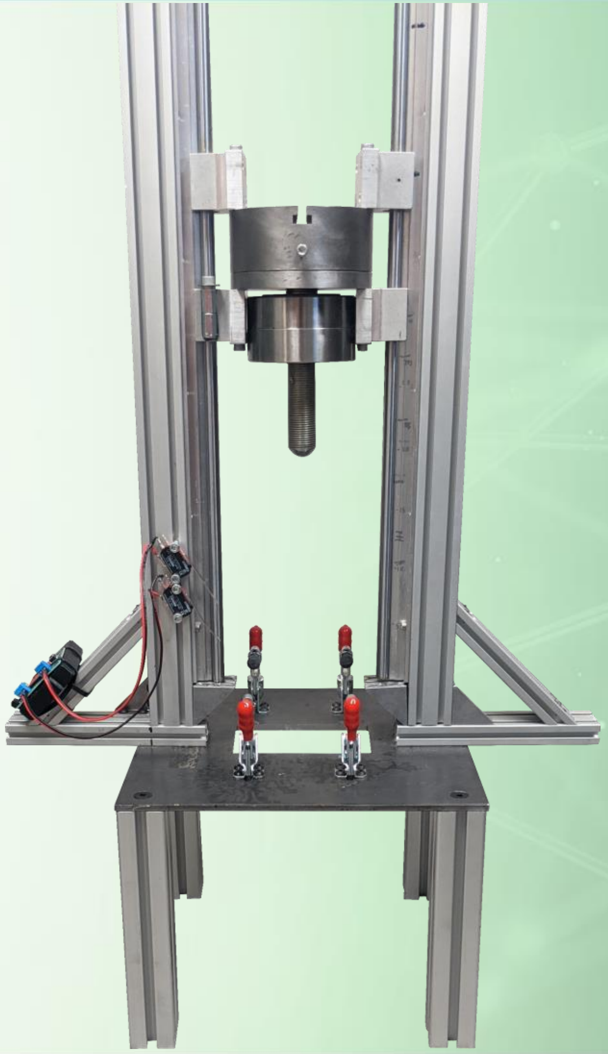
Initial impact energy is equal to the kinetic energy minus the retained strain energy



Drop tower

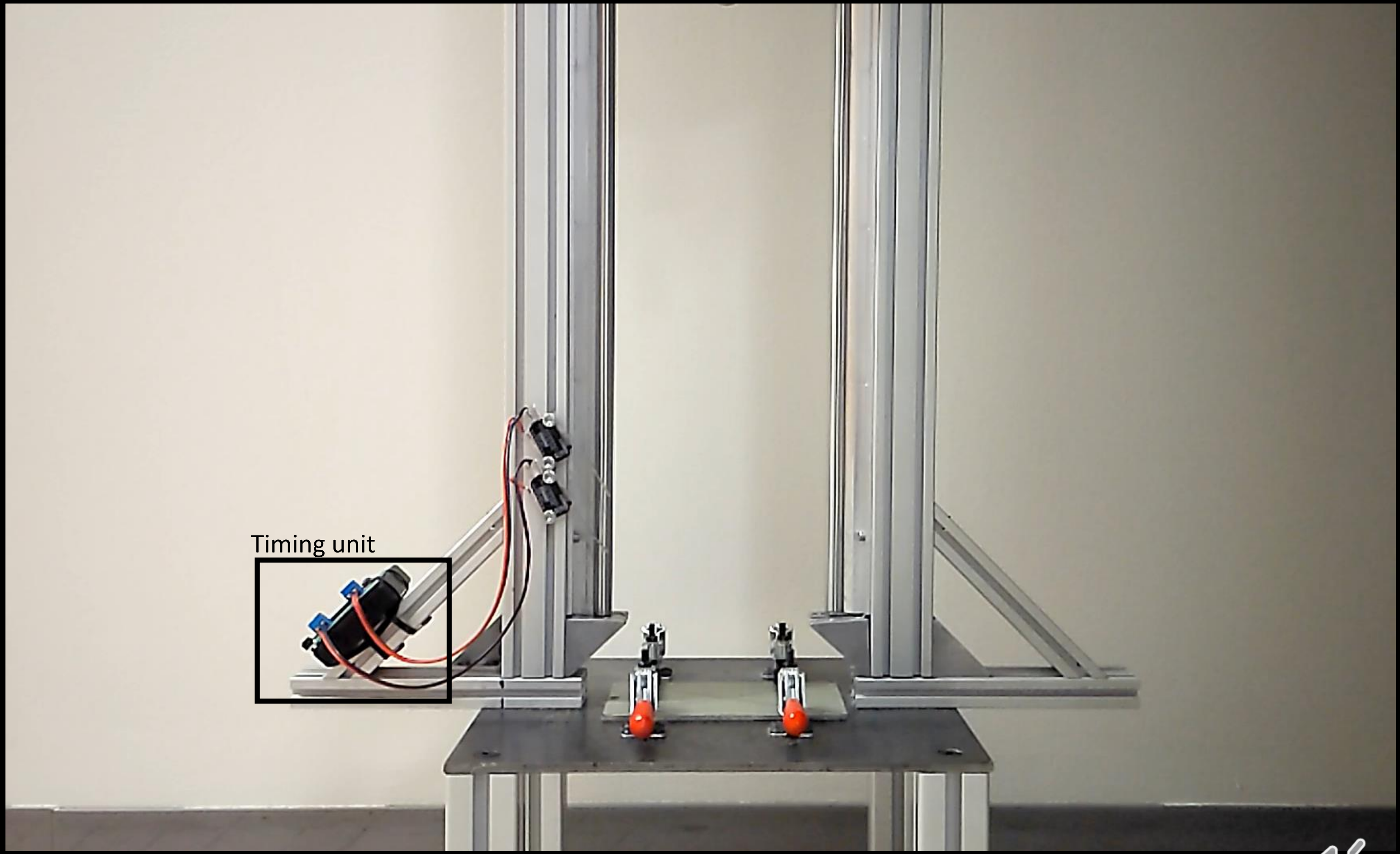
Specifications

- Impactor mass 6.5 kilograms
- Rail length 1 meter
- Maximum energy ≈ 20 joules
- Indenter Hemispherical



Drop tower

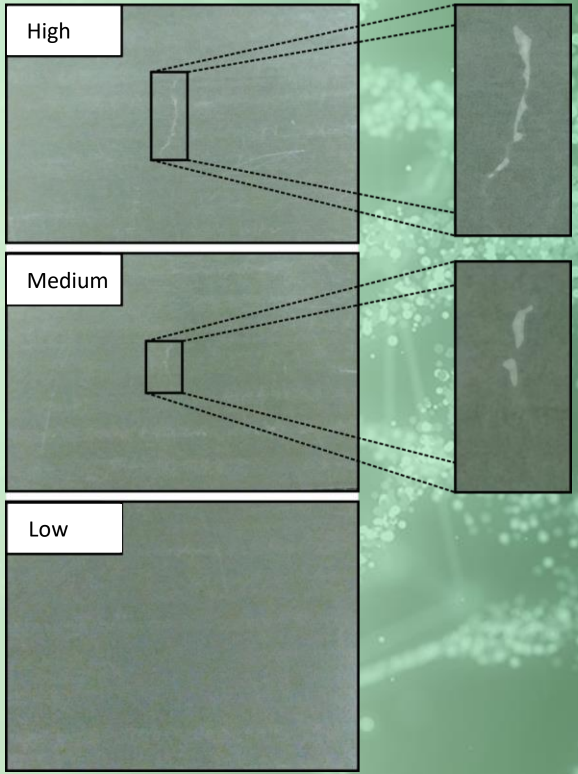
- Timer records in microseconds
  - For average velocity in the 3.5 cm before impact to calculate impact energy
- Impact caught before second rebound



Results

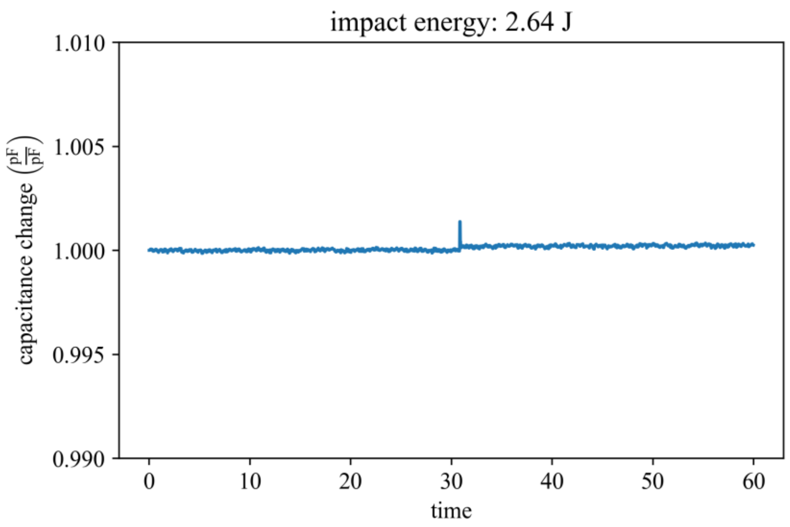
The GFRP was observed to respond in three domains:

- Pure elastic responses that are non-hysteric
- Small plastic deformations due to failure in the resin
- Larger deformations post-fracture where the Glass fiber fails

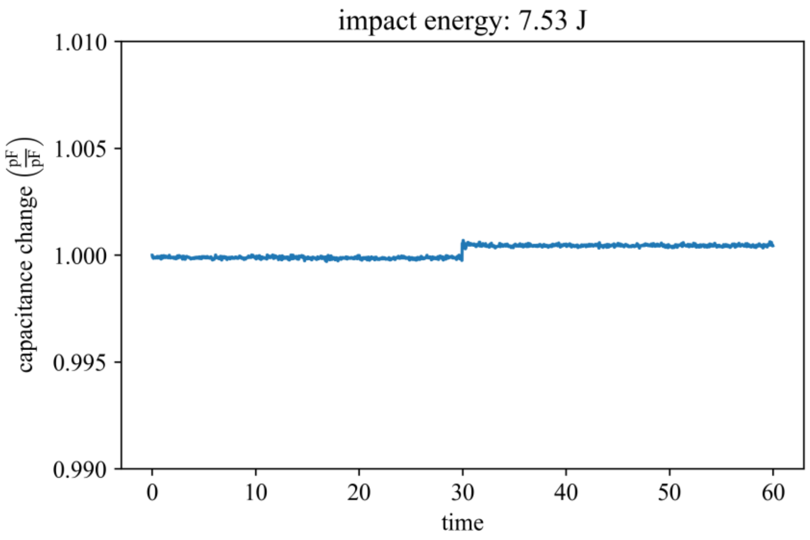


Identifying Damage

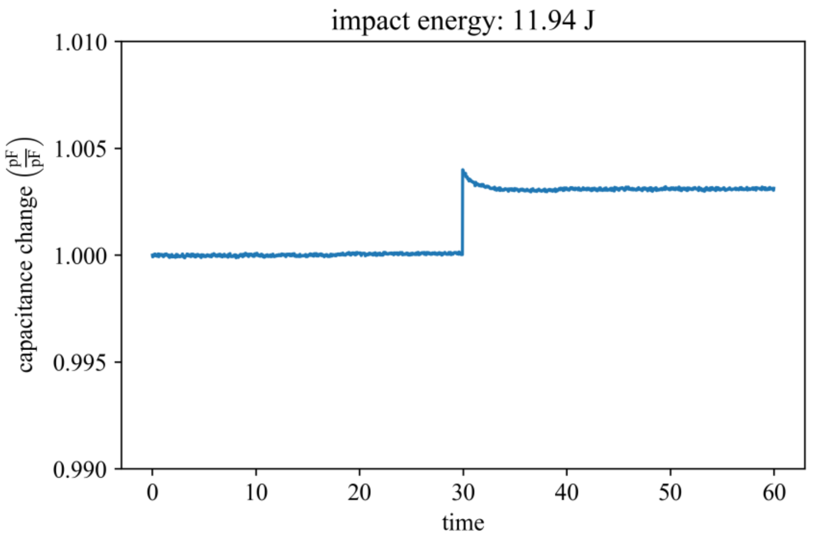
Results of a progression of impact energy.



Post impact no visible damage

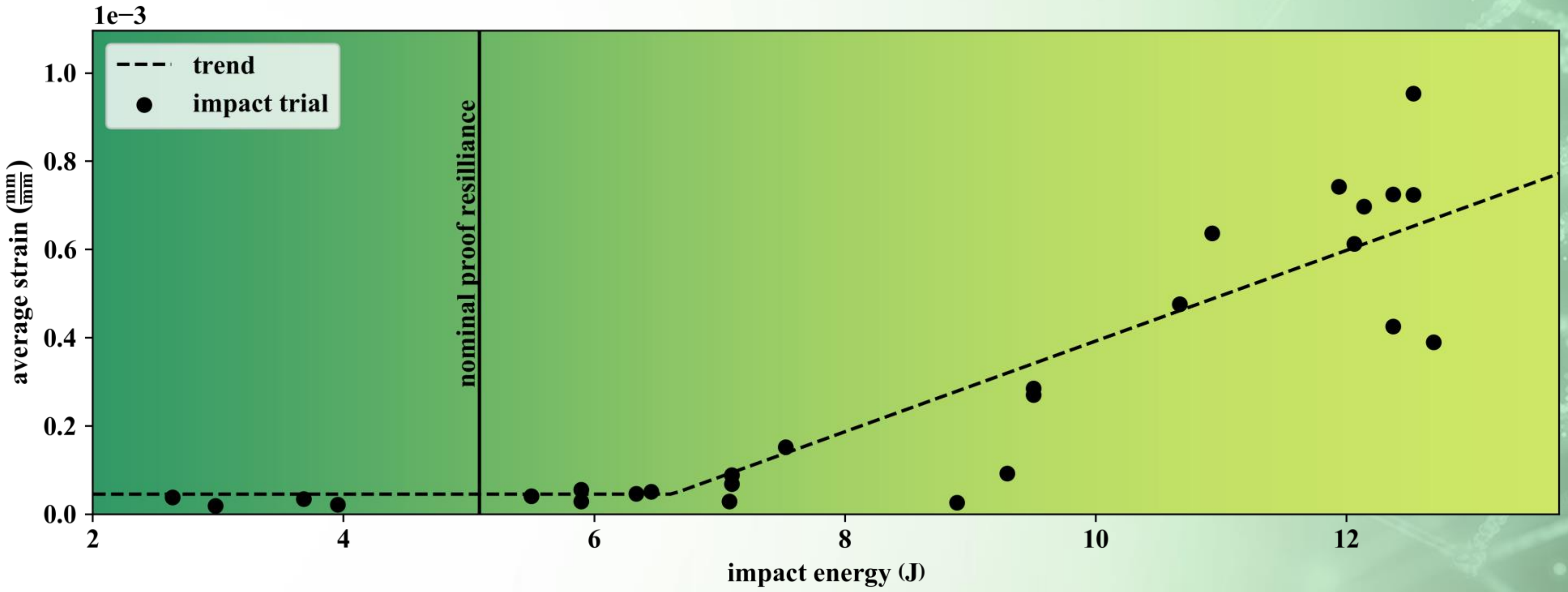


Post impact little visible damage



Post impact easily visible damage

Experimental Data



Conclusions

Impacts above the proof resilience were expected to store energy as deformations. These were registered in the SEC as a sustained increase in capacitance. Impacts below the nominal proof resilience showed little to no sustained change in capacitance by the SEC. These observations can be taken to show a positive evaluation for of the SEC in impact as a tool for impact detection and quantification.

Acknowledgements

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Further Reading on the SEC

- Li, Jian, et al. *Strain-based Fatigue Crack Monitoring of Steel Bridges using Wireless Elastomeric Skin Sensors*. No. FHWA-KS-19-01. 2019.
- Liu, Han, et al. "Numerical Investigation of Auxetic Textured Soft Strain Gauge for Monitoring Animal Skin." *Sensors* 20.15 (2020): 4185.
- Laflamme, Simon, and Jian Li. "Field Deployment of Sensing Skin on a Steel Bridge for Fatigue Crack Localization and Assessment." (2019).

THANKS

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